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AN APPROXIMATE HIGH-ENERGY ALPHA-PARTICLE-NUCLEUS-COLLISION MODEL*

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Abstract

An alpha-particle-nucleus-collision model, which assumes that the nucleons within the alpha particle can be treated separately and independently except for their relative spatial locations when they enter the nucleus, is described. Because of the assumptions that are made, calculations based on the model can be carried out using the intranuclear-cascade code of Bertini. Calculated data on the energy and angular distribution of emergent nucleons and on the cross sections for the production of various residual nuclei from alpha-particle-nucleus collisions are found to be in very approximate agreement with existing experimental data.

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I. INTRODUCTION

In order to perform shielding calculations for high-energy alpha particles arising from solar flares and particle accelerators, particle-production data from alpha-particle-nucleus collisions are required. In this note, a model for the prediction of the energy and angular distribution of nucleons from alpha-particle-nucleus collisions, as well as the cross sections for the production of various residual nuclei from alpha-particle-nucleus collisions, is described. In the model, it is assumed that these collisions may be simulated by transporting the nucleons of the alpha particles through the nucleus separately and independently except for their relative spatial location when they enter the nucleus. This assumption is a drastic oversimplification of the physical situation and is justified only by the fact that approximate agreement between calculated results and existing experimental data has been obtained. Because of the assumptions made, computations using the model may be obtained by direct application of the intranuclear-cascade code of Bertini.[1]

The model and the methods of computation using existing computer programs are described in Sec. II. The results obtained and comparisons with experimental data are discussed in Sec. III.

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II. DESCRIPTION OF THE MODEL

The intranuclear-cascade program of Bertini,[1] combined with the evaporation program of Dresner[2] as modified by Guthrie,[3,4] has been used extensively to predict with good reliability the results of nucleon-nucleus and pion-nucleus collisions. These existing programs have now been adapted to an alpha-particle-nucleus collision model.

In this model, shown schematically in Fig. 1, the nucleons comprising the alpha particle are arranged in a configuration similar to that of the deuteron, that is, two neutron-proton pairs separated by a fixed distance. The distance between the proton and the neutron in each pair is zero. The axis of the alpha particle (defined by the line joining the two pairs) is set perpendicular to the axis of incidence and parallel to the impact parameter p. The relative motion of the nucleons within the alpha particles has not been taken into account.

The alpha-particle nucleons are transported through the nucleus individually and independently except for their relative spatial locations when they enter the nucleus, and they are treated in the same manner as in the original cascade program.[1] Following the transport of the four nucleons, an alpha-particle collision occurs if at least one of the four nucleons transported interacts within the nucleus. The complete alpha-particle-nucleus interaction is then obtained from the accumulation of events associated with the four nucleons. The energy used in the cascade calculations for each nucleon comprising the alpha particle is obtained from the relation $(E_\alpha - B)/4$, where E_α is the incident alpha-particle energy and B is the binding energy of the alpha particle (~ 7 MeV/nucleon). B is a positive quantity and represents the amount of energy required to dissolve the alpha particle into its constituent

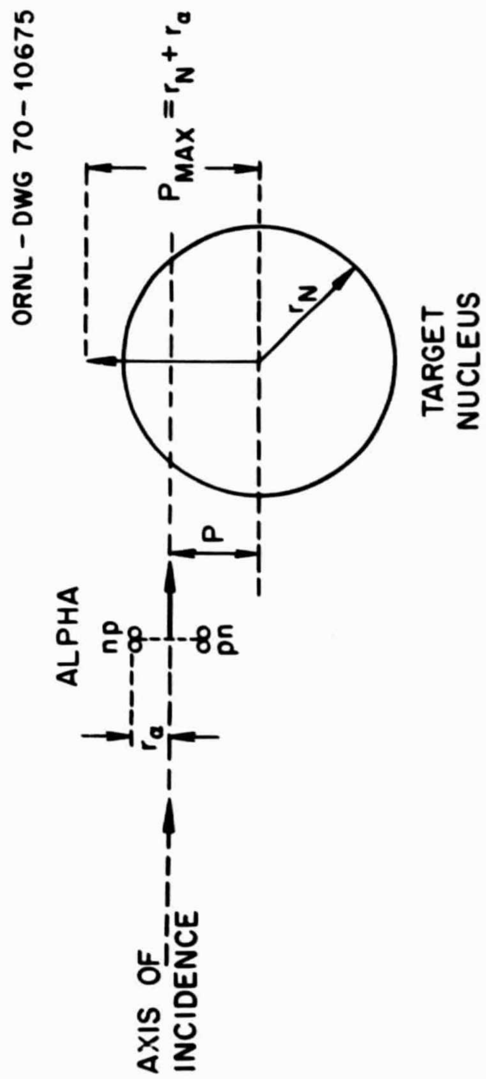

Fig. 1. Schematic Diagram of the Alpha-Particle-Nucleus-Collision Model.

nucleons. The nucleon energy is computed in this way because in the intranuclear-cascade code it is assumed that each nucleon acquires a binding energy of 7 MeV as it enters the nucleus.

The cross section is computed by assuming that the center of mass of the incident alpha particle is distributed uniformly over an area defined by $p_{max} = r_N + r_\alpha$, where r_N is the radius of the struck nucleus and r_α is the radius of the alpha particle. (For these calculations, $r_\alpha = 2.09$ F.) As the impact parameter approaches the edge of the nucleus (that is, $p \geq r_N - r_\alpha$), one of the proton-neutron pairs falls outside of the nucleus and only the two remaining nucleons have a nonzero probability to interact in the nucleus. At all impact parameters there is some probability that the four nucleons of the alpha particle will pass through the nucleus without interacting. Those Monte Carlo histories for which this occurs are used to compute an average nuclear transparency T, and the total nonelastic cross section σ is then computed from the formula

$$\sigma = \pi(r_N + r_\alpha)^2 (1 - T) .$$

After the four nucleons corresponding to an incident alpha particle have been transported through the nucleus, there usually remains a nucleus in an excited state. This nucleus can reduce its excitation by the emission of particles through evaporation. The evaporation code of Dresner[2] as modified by Guthrie[3,4] is used to determine the types, multiplicities, and energy distributions of the particles evaporated from the excited compound nucleus. The excitation energy used in the evaporation calculation for each incident alpha particle is obtained from the expression

$$EX = E_\alpha - \sum_i \epsilon_{\pi_i} - \sum_j (E_{N_j} + B') ,$$

where

ϵ_{π_i} = the total energy of the ith emitted pion,

E_{N_j} = the kinetic energy of the jth emitted nucleon,

B' = the binding energy of the least-bound nucleon in the nucleus, taken to be 7 MeV,

E_α = the kinetic energy of the incident alpha particle.

In an alpha-particle-nucleus collision, if one or up to three nucleons traverse the nucleus without interacting, these particles are then treated as cascade particles in that their energy is subtracted from the excitation energy. The residual nucleus A' and Z' values, which are used at the start of the evaporation portion of the calculation, are evaluated from the equations

$$A' = A + 4 - \sum_{n,p} 1$$

$$Z' = Z + 2 - \sum_{p,\pi^+} 1 + \sum_{\pi^-} 1 ,$$

where A and Z are the atomic number and charge of the original nucleus, respectively, and the sums are over the nucleons and pions that escape from the nucleus when the four nucleons corresponding to each incident alpha particle are transported through the nucleus.

III. RESULTS

All of the results presented below are on an absolute basis, and, with the exception of the selected alpha-particle radius, there are no adjusted parameters.

The computed energy spectra, including both the intranuclear-cascade and evaporation contributions of emergent protons and neutrons from the interactions of 205-MeV alpha particles with ^{27}Al and ^{108}Ag, are shown in Figs. 2 and 3 and Figs. 4 and 5, respectively. In Fig. 2 the computed proton and neutron spectra from the (α + ^{27}Al) interactions for the angular interval between 0 and 65° are shown. Comparison is made with the experimental proton spectral results of Bailey,[5] and the agreement is within a factor of ∿ 2 except in the last energy interval. Figure 3 gives the results for the wider angles corresponding to the angular interval from 100 to 180° for the same reaction. For these angles, the agreement between calculated and experimental results is remarkably good - within ∿ 30% over the energy range from 0 to 20 MeV. Figure 4 gives the computed neutron and proton spectra from the interaction (α + ^{108}Ag) for the angular interval 0 to 65°. Comparisons between the computed spectra and those of Bailey[5] are also within a factor of ∿ 2 except for the escaping nucleon-induced peak. For the wider angles shown in Fig. 5, agreement is also within a factor of ∿ 2 over most of the energy range considered. The experimental data used in these results were read directly from the curves presented by Bailey.[5] It should be noted that the computed cross sections for the backward angles arise principally from the evaporation mode.

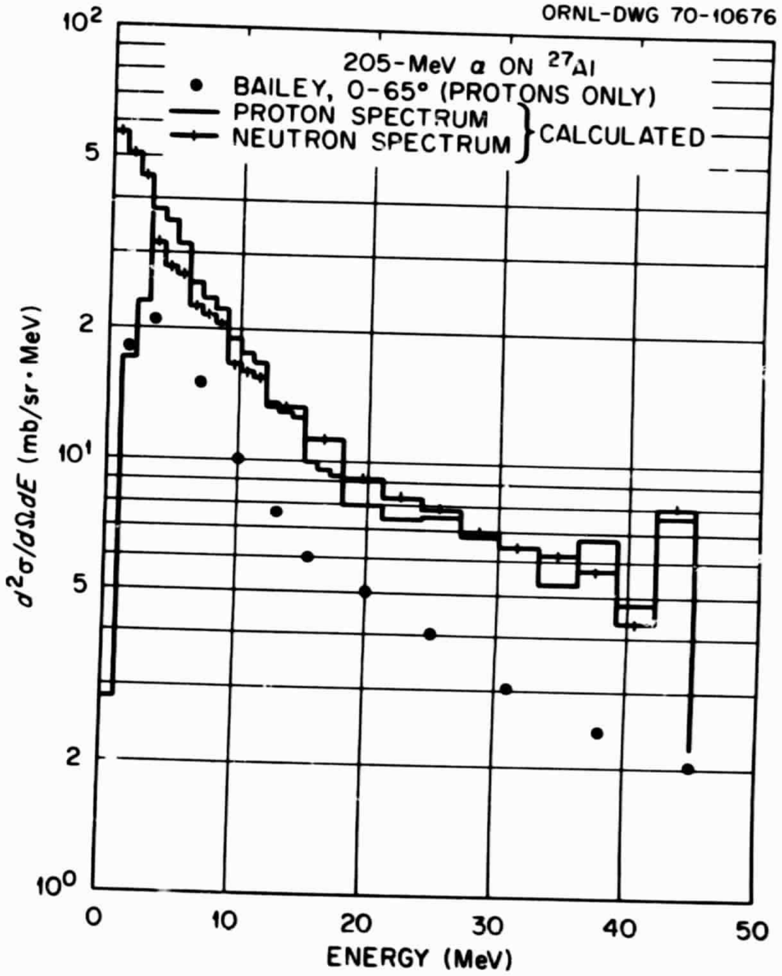

Fig. 2. Energy Spectra for Emergent Neutrons and Protons Averaged over the Angular Interval 0 - 65° from the Interaction of 205-MeV Alpha Particles with ^{27}Al.

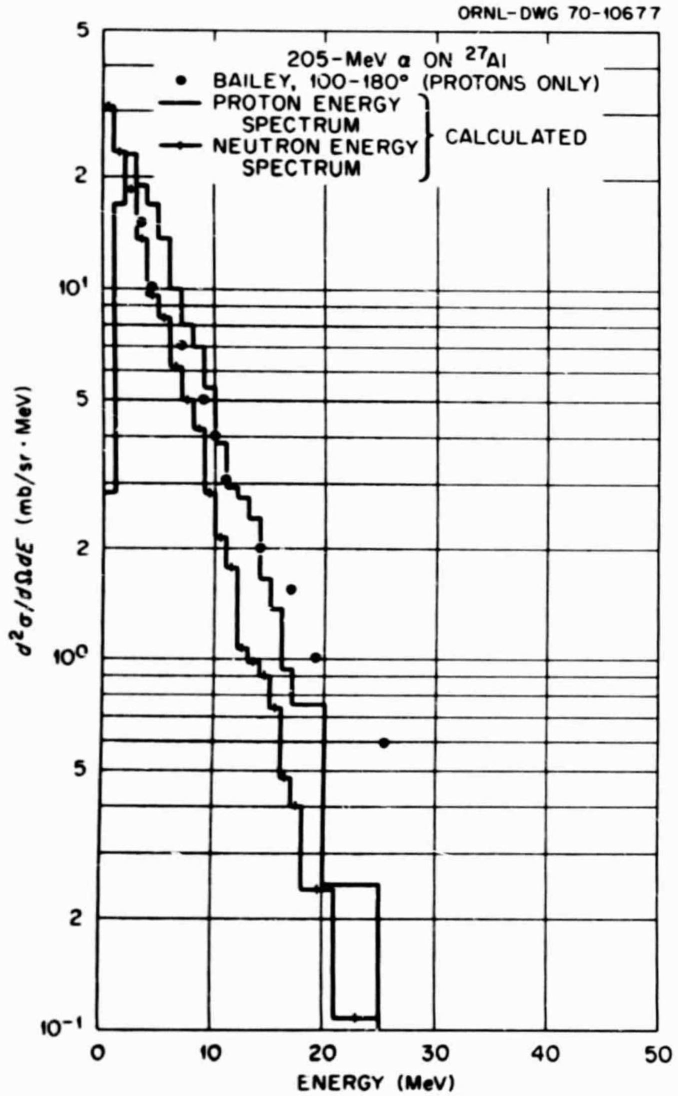

Fig. 3. Energy Spectra for Emergent Neutrons and Protons Averaged over the Angular Interval 100 - 180° from the Interaction of 205-MeV Alpha Particles with ^{27}Al.

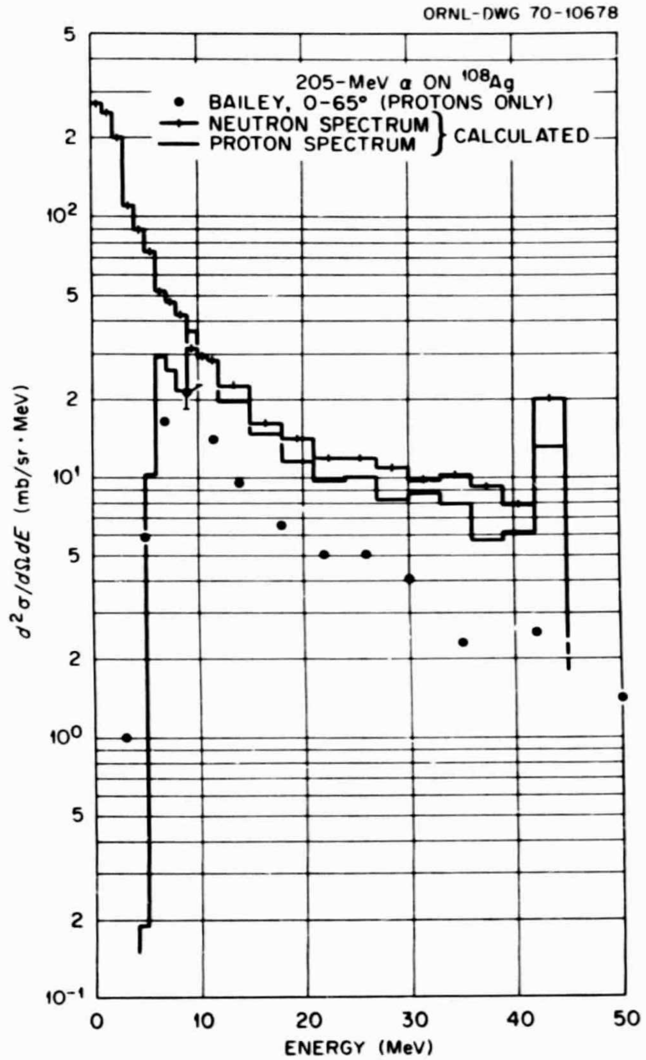

Fig. 4. Energy Spectra for Emergent Neutrons and Protons Averaged over the Angular Interval 0 - 65° from the Interaction of 205-MeV Alpha Particles with ^{108}Ag.

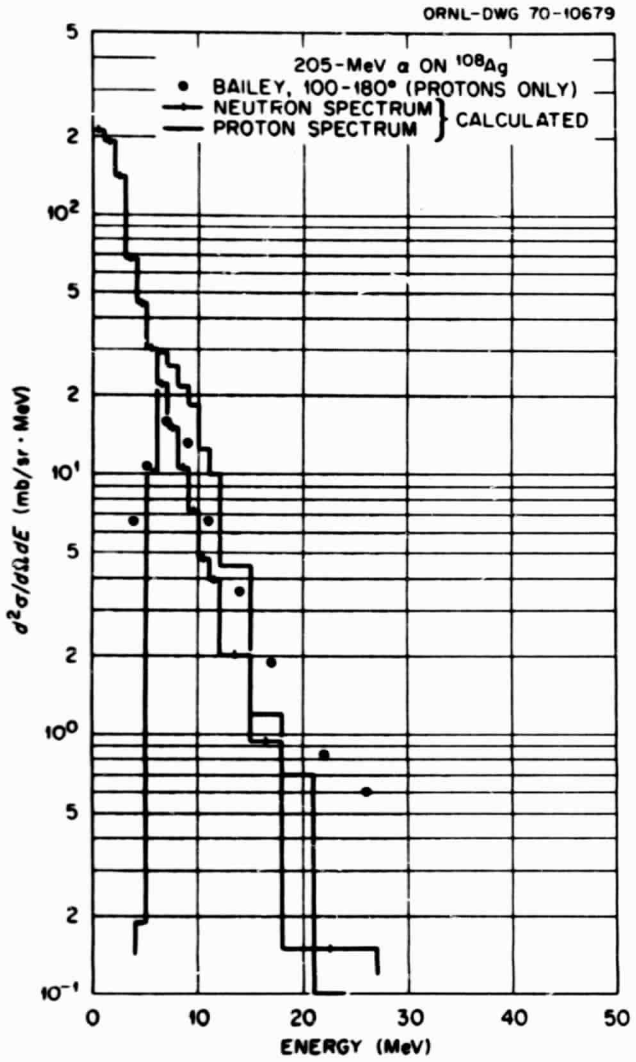

Fig. 5. Energy Spectra for Emergent Neutrons and Protons Averaged over the Angular Interval 100 - 180° from the Interaction of 205-MeV Alpha Particles with ^{108}Ag.

The peaks at high energies (last histogram interval in Figs. 2 and 4) in the neutron and proton spectra are the result of those histories in which one of the four alpha-particle nucleons emerges from the nucleus without interaction and the other three alpha-particle nucleons interact within the nucleus. It is important to note that these peaks do not include the uncollided nucleons from those incident alpha-particle histories in which only one or two of the alpha-particle nucleons collide in the nucleus. There is a substantial number of these nucleons, and if they were included in Figs. 2 and 4, the high-energy peaks would be unrealistically large. The presence of these uncollided nucleons is a serious defect of the model, but they may in a very approximate sense be identified with the deuterons, tritons, and ^{3}He's that are emitted from an alpha-particle-nucleus collision. If it is assumed that the reactions in which one or two of the alpha-particle nucleons collide in the nucleus correspond to stripping reactions in which the uncollided nucleons proceed as a unit, then it is possible to obtain a very approximate estimate of the deuteron, triton, and ^{3}He multiplicities from the collision. The computed total cross sections for the production of these particles and the cross sections for the production of neutrons, protons, and alpha particles from the (α + ^{27}Al) and (α + ^{108}Ag) reactions are given in Table I. Data are presented for both the forward and backward angles, and comparison is made with the experimental results of Bailey.[5] The calculated cross sections were obtained by integration between the lower energy limit specified in the experiment to the upper energy limit obtained in the calculations. For the backward angles where the evaporation contribution dominates, the data are in reasonable agreement. However, for the forward angles, all of the calculated results, except for the

TABLE I

Integrated Cross Sections for Emergent Particles
(mb/sr)

Target	Angular Interval	Protons (3-105 MeV) Cal.[a]	Protons Exp.[b]	Deuterons (1.5-53 MeV) Cal.[a]	Deuterons Exp.[b]	Tritons (1-35 MeV) Cal.[a]	Tritons Exp.[b]	^{3}He Particles (4-140 MeV) Cal.[a]	^{3}He Exp.[b]	Alpha Particles (3-105 MeV) Cal.[a]	Alpha Exp.[b]
Al	0 - 65°	466	277	212	54	79	11.5	72	10.6	27.2	138
	100 - 180°	135	94.5	10.2	19.4	1.68	3.66	2.32	1.63	27.2	34.5
Ag	0 - 65°	527	304	343	36.9	96	10.1	73	8.37	16.2	104
	100 - 180°	147	130	9.8	14.8	1.5	4.1	0.14	0.84	16.2	43

a. Lower integration limits are the same as those of Bailey.[5]

b. Values of Bailey.[5]

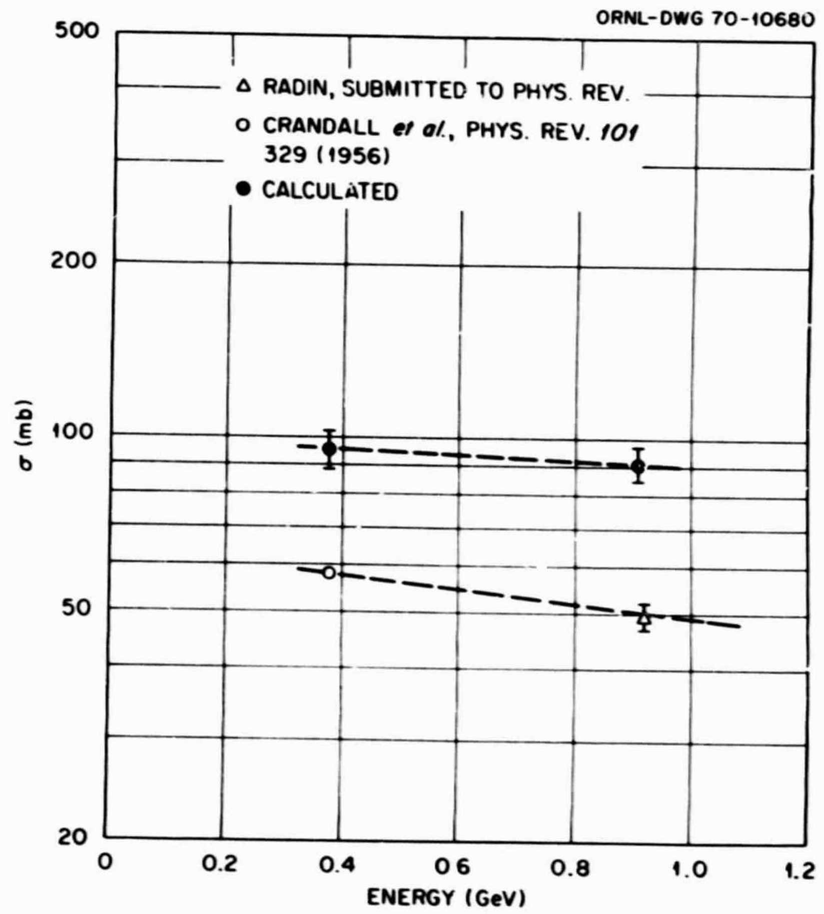

Fig. 6. Radiochemical Cross Sections for the Production of $^{11}_{6}C$ from the Reaction (α + ^{12}C) as a Function of Incident Alpha-Particle Energy.

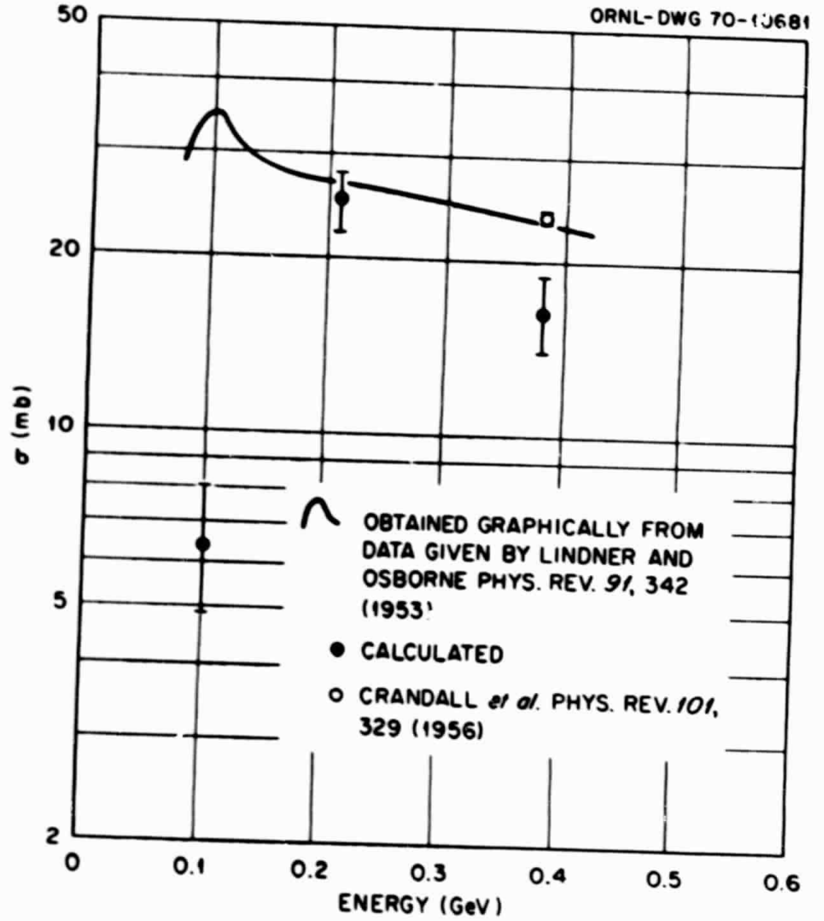

Fig. 7. Radiochemical Cross Sections for the Production of $^{24}_{11}Na$ from the Reaction (α + ^{27}Al) as a Function of Incident Alpha-Particle Energy.

alpha-particle cross sections, are higher than the experimental values. This is not unreasonable since, except for the evaporation mode, it is not possible to obtain emergent alpha particles. The difference between the forward and backward calculated cross sections for deuterons, tritons, and ^3He particles gives the cross section for the production of these particles due to stripping reactions. Of course, this model grossly overestimates these cross sections and can give no estimate of the energy distribution of these particles. The deuterons, tritons, and ^3He particles produced in this manner will have in the present model energies of $2(E_\alpha - B)/4$, $3(E_\alpha - B)/4$, and $3(E_\alpha - B)/4$, respectively.

Figures 6 and 7 give the results of calculations to determine the radiochemical cross sections for the interactions of alpha particles with ^{12}C and ^{27}Al, respectively. For the reaction (α + ^{12}C), Fig. 6, the results are within a factor of 2 in agreement with the experimentally measured cross sections of Crandall et al.[6] and Radin.[7] Figure 7 gives the calculated radiochemical cross sections for the production of ^{24}Na through the (α + ^{27}Al) reaction. These results, though somewhat sparse, are indicative of the behavior of the cross section with alpha-particle energy. Agreement at 210 MeV is quite good, within the statistical limits of the experimental results of Lindner and Osborne.[8] At 100 MeV the calculated results are low. This is expected since the computational model cannot work satisfactorily for low alpha-particle energies where the relation $(E_\alpha - B)/4 \gtrsim 50$ MeV.

Extensive calculations have been made to compute radiochemical cross sections for the reaction (α + ^{93}Nb) at incident alpha-particle energies of 348, 528, 748, and 910 MeV. The results of the calculations are given in Figs. 8-12. Also shown in the figures are comparable data obtained with the intranuclear-cascade program[1] for the reaction (p + ^{93}Nb) for protons

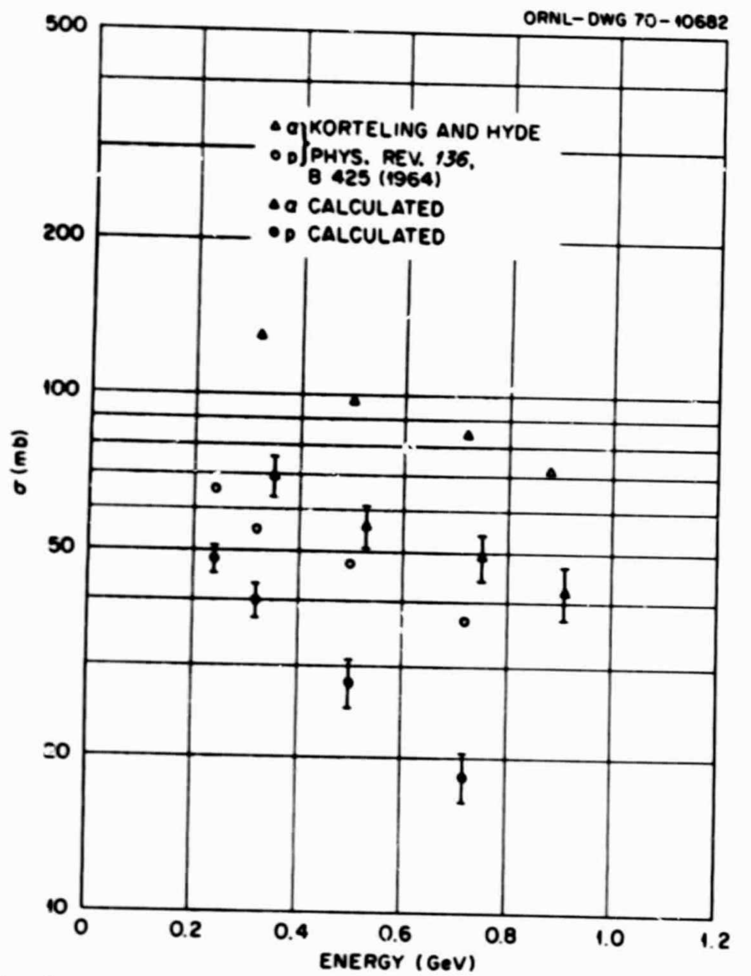

Fig. 8. Radiochemical Cross Sections for the Production of $^{90}_{41}$Nb from the Reactions (α + ^{93}Nb) and (p + ^{93}Nb) as a Function of Incident Alpha-Particle Energy.

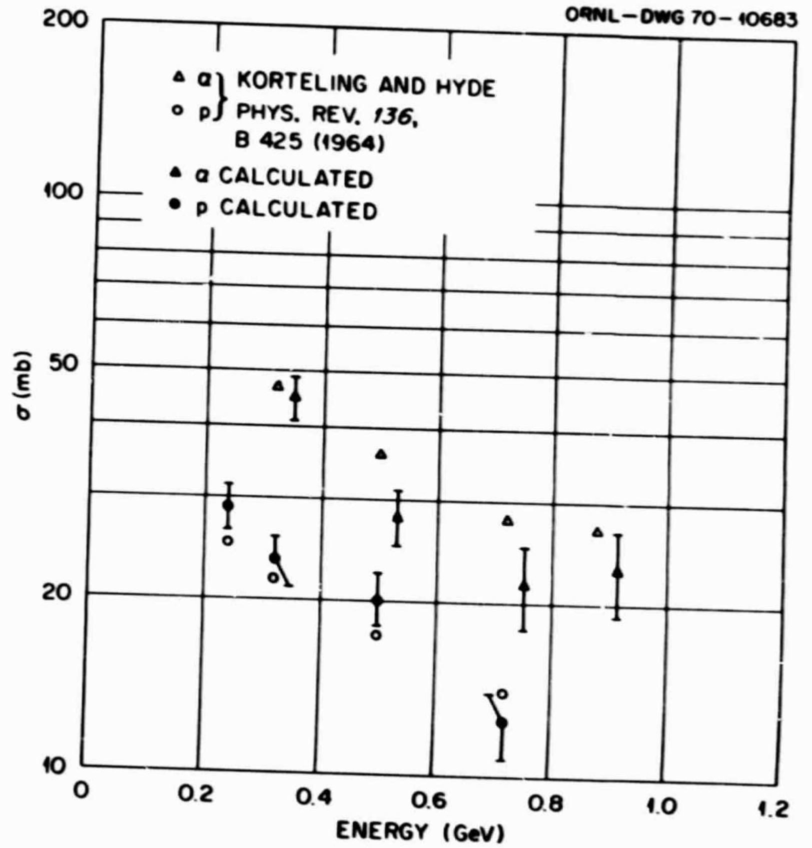

Fig. 9. Radiochemical Cross Sections for the Production of $^{89}_{41}$Nb from the Reactions (α + ^{93}Nb) and (p + ^{93}Nb) as a Function of Incident Alpha-Particle Energy.

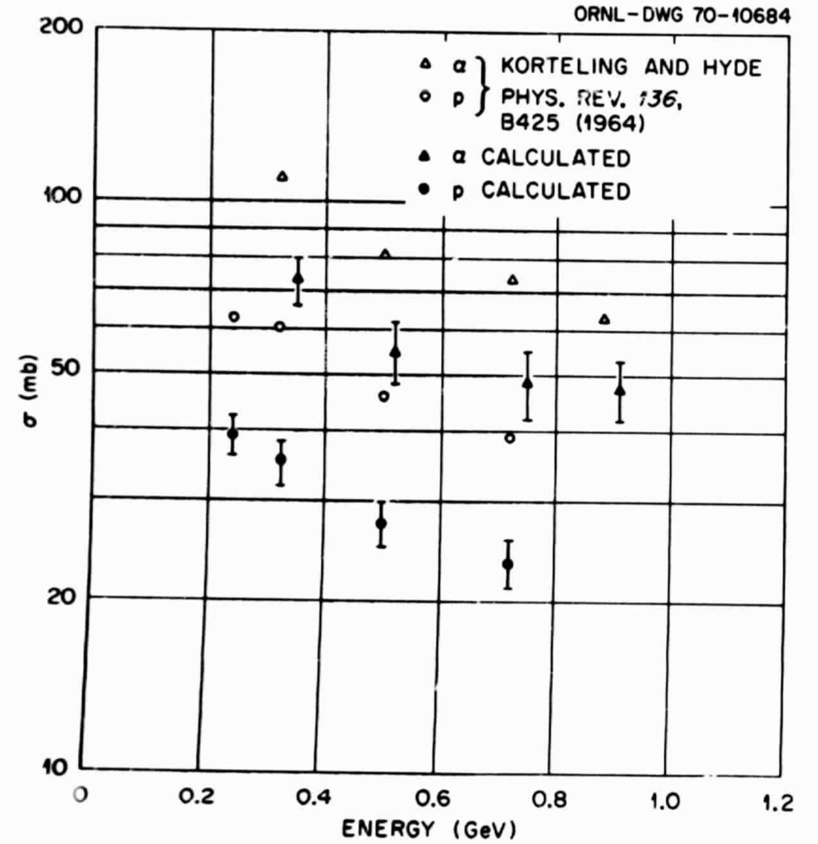

Fig. 10. Radiochemical Cross Sections for the Production of ${}^{89}_{40}Zr$ from the Reactions (α + ${}^{93}Nb$) and (p + ${}^{93}Nb$) as a Function of Incident Alpha-Particle Energy.

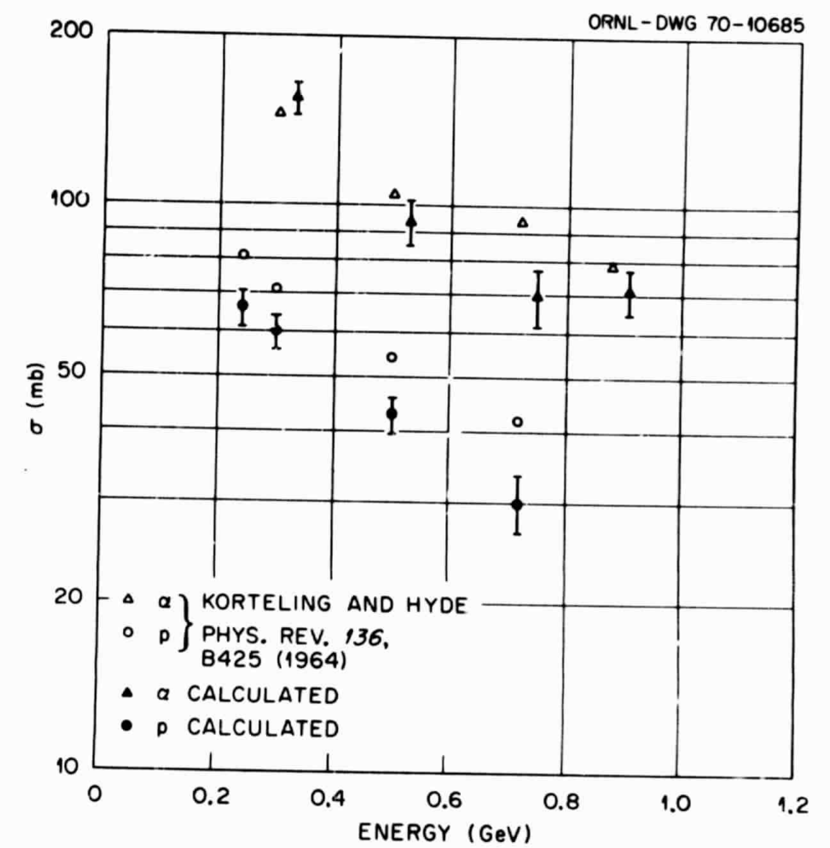

Fig. 11. Radiochemical Cross Sections for the Production of ${}^{88}_{40}Zr$ from the Reactions (α + ${}^{93}Nb$) and p + ${}^{93}Nb$) as a Function of Incident Alpha-Particle Energy.

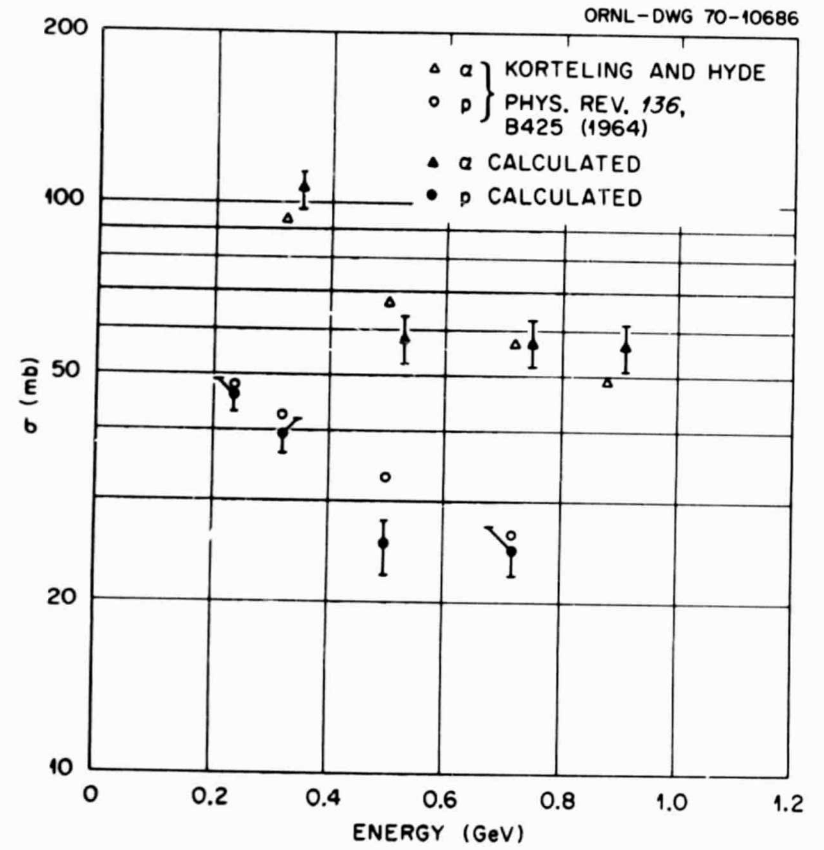

Fig. 12. Radiochemical Cross Sections for the Production of $^{87}_{40}$Zr from the Reactions (α + ^{93}Nb) and (p + ^{93}Nb) as a Function of Incident Alpha-Particle Energy.

of approximately the same energy. Comparisons are made with the experimental results of Korteling and Hyde.[9] With the exception of the reactions leading to the nuclides $^{90}_{41}$Nb and $^{89}_{40}$Zr, experimental results and calculated cross sections are in favorable agreement, and the alpha-particle results are in slightly better agreement than the proton-nucleus-collision results. The computed cross sections for the production of $^{90}_{41}$Nb and $^{89}_{40}$Zr, Figs. 8 and 10, show disagreement with experimental results[9] of a factor of 1.5 and more. The proton data also show similar differences.

In Fig. 13 the calculated inelastic cross sections for the (α + ^{93}Nb) and (p + ^{93}Nb) reactions are plotted as a function of incident-particle energy. In the inset in the figure, the ratio $(\sigma_\alpha/\sigma_p)_{inelastic}$ is tabulated. Comparisons are made with the results given by Korteling and Hyde[9] and are shown to be in good agreement. These authors did not measure the inelastic cross section. However, since all the partial cross-section ratios between alpha-particle and proton reactions are ~ 2, it seems reasonable to expect the ratio of the inelastic cross sections to behave in the same way. It should be noted that the decrease in the ratio with increased energy probably arises from the production of pions in the proton case causing a larger proton-nucleus inelastic cross section. It is more likely that a 500-MeV nucleon will produce a pion than will a 500-MeV alpha particle.

In Table II the production cross sections for several radionuclides resulting from interactions of alpha particles with ^{93}Nb for E_α = 720 and 880 MeV and protons at E_p = 720 MeV are shown. The nonzero results differ from experimental results by as much as a factor of 10. The large differences between calculated results and experimental data are not entirely

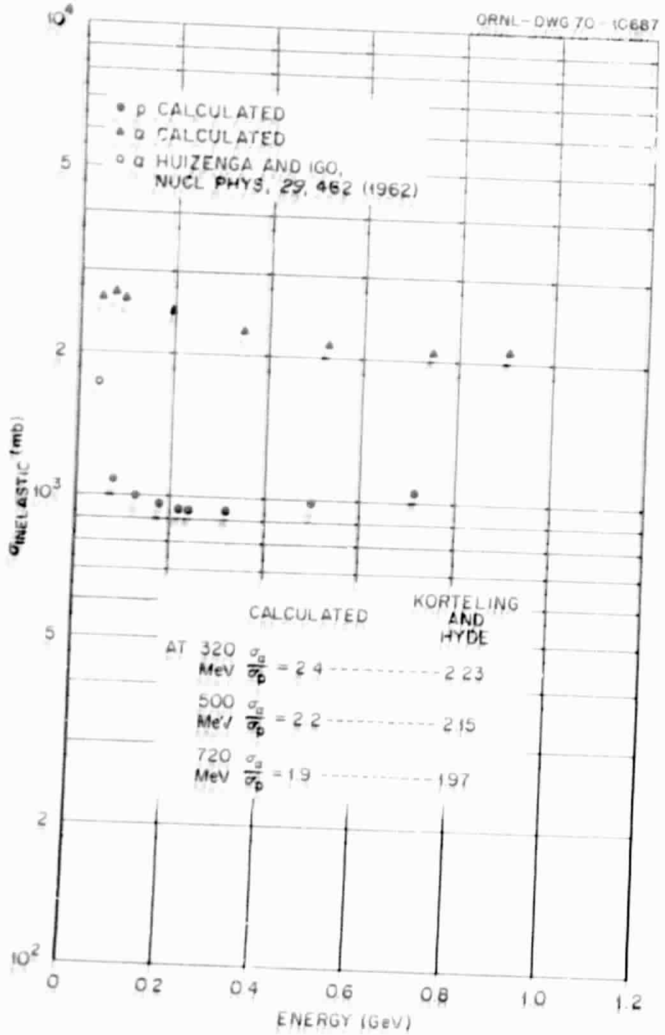

Fig. 13. Calculated Inelastic Cross Sections for the Reactions (α + ^{93}Nb) and (p + ^{93}Nb) as a Function of Incident-Particle Energy. The values of Korteling and Hyde represent the averaged ratio of the radiochemical cross sections obtained for alpha particles and protons.

TABLE II

Calculated and Experimental Radiochemical Cross Sections for the Production of the Listed Nuclides for 720- and 880-MeV Alpha Particles and 720-MeV Protons Incident on ^{93}Nb (mb)

	α + ^{93}Nb (720 MeV)		p + ^{93}Nb (720 MeV)		α + ^{93}Nb (880 MeV)	
Nuclide	Cal.[a]	Exp.[b]	Cal.[c]	Exp.[b]	Cal.[d]	Exp.[b]
$^{67}_{29}$Cu	0.0	0.166	0.0	0.12	0.0	0.257
$^{64}_{29}$Cu	4.49	4.34	1.53	2.82	5.61	6.26
$^{61}_{29}$Cu	3.37	2.59	0.17	1.74	8.89	4.75
$^{66}_{28}$Ni	0.0	0.019	0.0	0.008	0.0	0.029
$^{65}_{28}$Ni	0.0	0.121	0.0	0.063	0.0	0.167
$^{57}_{28}$Ni	0.56	0.143	0.0	0.074	2.8	0.242
$^{24}_{11}$Na	0.0	0.30	0.0	0.131	0.0	0.533
$^{22}_{11}$Na	0.0	0.196	0.0	0.066	0.0	0.254

a. For these calculations, E_α = 748 MeV.

b. R. G. Korteling and E. K. Hyde, Phys. Rev. 91, 324 (1953).

c. Values of Bertini.[1]

d. For these calculations, E_α = 910 MeV.

unexpected for residual nuclei far removed from the parent nucleus (see Ref. 1). Since fragmentation has not been included in the evaporation programs,[2-4] the zero cross sections predicted for ^{22}Na and ^{24}Na were expected at these energies. The remaining cross sections having zero values are due primarily to the statistical nature of the calculations.

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